ARMY RESEARCH LABORATORY

Feasibility of a 7,000-lb 155-mm Towed Howitzer

Lawrence W. Burton
Christopher P. R. Hoppel
Robert P. Kaste

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Lawrence W. Burton, Christopher P. R. Hoppel, and Robert P. Kaste

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An investigation was undertaken to determine a sensible design weight for a lightweight howitzer. After choosing 7,000 lb (3,175 kg) as a design goal, a study was undertaken to ascertain the feasibility of such a system while attempting to maintain 155-mm range and lethality.

Work done previously by the U.S. Army Research, Development, and Engineering Center (ARDEC) and the Materials Testing Laboratory (MTL) on reducing the weight of various howitzer components is reviewed. Techniques being employed by various organizations currently developing 9,000-lb howitzers are also presented. These are meant to provide a precursory look at what has been done by others to minimize the weight of a 155-mm artillery system.

Details of the estimated weight savings attributable to composite replacement parts, incorporation of a soft recoil system, and restricting the maximum charge to the M119A2 are presented to demonstrate the possibility of a 7,000-lb lightweight 155-mm howitzer. While such a weapon does not have a range capability equivalent to the current M198 155-mm system, it would bring an upgraded firepower capability to the light maneuver forces, who presently use 105-mm artillery, and increase the current engagement range.

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1. INTRODUCTION

The roles of field artillery on the battlefield include providing a deep-strike capability, allowing for fire in all weather and terrain, and having the ability to mass fires without moving the weapon platforms. An important requirement for field artillery is that it must be at least as mobile as the unit that it supports. Such a prerequisite poses a dilemma for the light maneuver forces, which need a very mobile artillery piece and typically must sacrifice both range and lethality in the interest of mobility. Recognition of this difficulty resulted in a study being initiated to determine what size howitzer was most beneficial and practical to the U.S. Army light forces.

At present, the M198 155-mm howitzer is the centerpiece of towed U.S. artillery systems. However, with a mass of 15,800 lb (7,167 kg) it is not a viable weapon for the light forces. In recent years there has been substantial effort to develop a much lighter 155-mm howitzer. Two British contractors, Royal Ordnance and Vickers Shipbuilding and Engineering Limited (VSEL), have each designed and tested 155-mm cannon prototypes with weights of approximately 9,000 lb (4,082 kg). Also, the Advanced Towed Cannon Artillery System (ATCAS) program was established by the U.S. Army and Marine Corps to develop a Joint Operational Requirements Document (JORD) for a lightweight 155-mm towed howitzer. However, even a towed howitzer on the order of 9,000 lb is still too heavy to be of interest to the light forces artillery.

Thus, a study to identify what weight towed howitzer would provide sufficient maneuverability while maintaining 155-mm firepower was undertaken. After identifying a desired system weight for a light forces howitzer, attempts were made to quantify the weight savings achievable due to improved recoil techniques, substitution of lightweight materials, and reduced chamber pressure requirements. The details of these tradeoffs and the projected performance of a very lightweight howitzer are reported here.

1.1 Logistical Study. In order to make sound decisions on the desirable features of a lightweight 155-mm howitzer, it is first imperative to determine what "lightweight" means. A review of past and present towed howitzers was made to determine their mass and vehicle towing requirements.

Table 1 provides a listing of various towed howitzers, their total weight, the maximum firing range of both nonassisted and rocket-assisted (RA) projectiles, and the size vehicle typically used to transport the weapon system on the ground (Foss 1993). The 105-mm M119, the replacement howitzer for the

Table 1. U.S. Army Howitzers - Characteristics and Performance

Howitzer	Caliber (mm)	Weight (lb)	Tow Vehicle (Truck)	Range	
				Nonrocket Assist (m)	Rocket Assist (m)
M102	105	3,300	HMMWV	11,500	15,100
M119	105	4,100	"heavy" HMMWV	14,000	20,100
M114	155	12,800	5 ton	14,600	19,300
M198	155	15,800	5 ton	22,000	30,300

M102, is currently in service and available to the light forces. It provides a very light system but lacks the firepower and lethality of the 155-mm M198 system.

The M114 listed was the predecessor to the M198 as the Army's 155-mm main artillery weapon. It is interesting to note that while the M114 is 3,000 lb lighter than the M198, it provides no logistical benefit because it still requires a 5-ton truck for transport on the battlefield.

To be of benefit to the light force community, a lightweight howitzer with a 155-mm bore, towable by a 2.5-ton truck would be preferred. Various transport vehicles currently in service were examined. Table 2 gives details of four such vehicles and provides vehicle weight along with towing capacity over both road and cross-country conditions (Jane's Information Group Limited 1986). Note that the 2.5-ton truck is not a transport option unless the howitzer weighs less than 10,000 lb (4,535 kg). The 9,000-lb howitzers detailed previously meet this requirement; however, they would be restricted to primarily road transport. Ideally, a 155-mm system weighing 6,000 to 7,000 lb would be desirable to allow for off-road transport.

The fundamental purpose of lightweight systems is to provide greater mobility and improve deployability. The C-130 is the primary fixed-wing aircraft used by the Army for tactical air transport operations. It has an allowable cabin load of 25,000 lb (11,340 kg) (Headquarters, Department of the Army 1993). The UH-60 Blackhawk utility helicopter is the Army's rotary-wing aircraft most frequently employed to deliver cargo and equipment. The Blackhawk is capable of externally carrying 8,000 lb (3,629 kg) via sling lift (Headquarters, Department of the Army 1986).

Table 2. Tow Vehicles for U.S. Army Howitzers

Vehicle	Type	Vehicle Weight (lb)		Maximum Towed Load (lb)	
		Empty	Loaded, Road	Road	Cross-Country
M939	5 ton	22,000	32,000	—	15,000
M36A2	2.5 ton	15,200	25,300	10,000	6,000
HMMWV	multipurpose	5,300	7,700	3,400	2,400
"heavy" HMMWV	multipurpose	5,600	8,000	4,200	—

Table 3 shows combinations of weapon weights and their prime movers transportable by a C-130 based on Tables 1 and 2. It also indicates if the howitzer can be transported by a UH-60. The data shown in the table only account for the weight of the systems. It is recognized that the volumetric cube size also plays a role in determining the number of systems transportable by an aircraft. Previous work examining the weight and cube of 155-mm howitzers and their prime movers concluded it was improbable to transport both systems in the same load aboard a C-130 aircraft (Fortier 1995).

Table 3. Summary of Towed Howitzer Transportability

System	System Weight (lb)	Tow Vehicle (Weight)	No. of Systems Liftable	
			C-130	Blackhawk
M198	15,800	5-Ton Truck (22,200 lb)	Truck: 0 M198: 1	M198: 0
LWT 155-mm	7,000	2.5-Ton Truck (15,200 lb)	Truck: 1 155 mm: 1	155 mm: 1
M119	4,100	"heavy" HMMWV (5,600 lb)	Truck: 2 M119: 3	M119: 1

Table 3 shows the benefits of a lightweight 155-mm towed howitzer. The weight of the lightweight system was chosen as 7,000 lb (3,175 kg) to allow for off-road transportation by a 2.5-ton truck in all except the most extreme conditions. At this weight plateau, the lightweight 155-mm becomes equivalent, from a logistics standpoint, to the M119 105-mm howitzer, in that it may be lifted by the Blackhawk

helicopter. Also, the 7,000-lb lightweight system could be transported with its prime mover, a 2.5-ton truck, on a C-130, thus providing for a more efficient transport than the M198. These facts make such a system beneficial to the light forces. Thus, 7,000 lb was established as the goal weight for a lightweight 155-mm towed howitzer. The tradeoffs required to reach this goal weight are detailed in the following sections.

1.2 Lightweight Material Substitution. Several previous investigations attempting to reduce the weight of specific parts in towed howitzer systems have been conducted. The U.S. Army Materials Technology Laboratory (MTL)* studied the effects of optimizing the weight of the M198 trails (U.S. Army Materials Technology Laboratory 1982). In the MTL study, the trails were designed as tapered box beams, with a length of 110 in (2.8 m), and were able to withstand the shear and bending loads imposed by a cookoff loading condition. The analytic investigation resulted in the lightest trail weight design using steel, aluminum, and several different composite materials. The resulting design weights are summarized in Table 4.

Table 4. Trail Weight for a 155-mm Lightweight Towed Howitzer

Material System	Trail Weight (lb/kg)
High Strength Steel	518/235
High Strength Aluminum	362/164
Glass-Fiber-Reinforced Epoxy	185/84
Graphite-Fiber-Reinforced Epoxy	114/52
Combination of Graphite-Fiber-Reinforced Epoxy and Kevlar-Fiber-Reinforced Epoxy	106/48

The weights predicted in this study are much lower than the present weight, 927 lb (420 kg), of the M198 trails. It should be noted that these trails were only designed for the loads associated with firing at peak pressure. Issues such as loads due to towing and durability were not addressed. Therefore, the

* The Materials Technology Laboratory (MTL) has since been reorganized as the Materials Directorate of the U.S. Army Research Laboratory.

trail weights for a fielded system may be higher than those shown in Table 4. However, it is significant to note the lightest composite design shows an 80% weight savings over the steel system and a 70% weight savings over an aluminum system.

In the mid-1980s, MTL also investigated the use of composite materials to reduce the weight of the M102, 105-mm towed howitzer (Cavallaro 1994; Ghiorse 1995; Oplinger 1995). This program used material substitution to reduce the weight of several key components in the gun; however, the final system was not built because the effects of component weight reductions on recoil and weapon stability were not considered in the design.

One significant accomplishment from this program was a lightweight composite cradle for the M102 (Cavallaro et al. 1992). The cradle was manufactured with graphite-fiber-reinforced epoxy and Rohacell foam core. Static and fatigue tests were performed on the cradle to simulate the loads generated during a gun firing (towing and transportation loads were not considered). The composite cradle had the same static strength and much better fatigue performance than the fielded M102 cradle.

In a separate project, the U.S. Army Armament Research, Development, and Engineering Center (ARDEC) performed a paper study on how to reduce the weight of specific component parts on the M198 howitzer by replacing steel with either titanium, boron-fiber-reinforced aluminum, or graphite-fiber-reinforced epoxy. A Pro Engineer computer-aided design model (Fire Support Armaments Center 1995) of the M198 was constructed, and each component was subsequently evaluated for possible weight reduction. The reduced weights for the parts are listed in Table 5. This effort shows the system component weight can be reduced 20%, for a weight savings of 3,288 lb (1,491 kg). However, this study was limited in scope in that it only examined modifications to the existing M198 weapon platform and did not consider changes to the recoil components, which account for 45% of the system's total weight. Also, the effects of changing the howitzer's center of gravity as a result of material substitution were neglected. Any change in these areas would require alteration of the entire gun structure.

1.3 The 9,000-lb Class Howitzers. While the goal of this study was to strive for a 7,000-lb howitzer, it is important to examine what is currently being done by several groups hoping to attain a 9,000-lb system. In doing so, it was hoped that hurdles to weight reduction beyond the 9,000-lb plateau could be identified.

Table 5. Weight Reduction of M198 Howitzer Components

No. of Components	Current Weight (lb)	Modified Weight (lb)	Total Weight Savings (lb)	Factors Affecting Future Reductions
Equilibrator (2)	128 each (steel)	102 each (Ti)	52	Height of the Gun
Speed Shift	104 (steel)	68 (Ti)	36	—
Actuator	47 (steel)	31 (Ti)	16	—
Traversing Mechanism	67 (Al and steel)	48 (Al and Ti)	19	—
Friction Clutch	47 (Al and steel)	34 (Al and Ti)	13	—
Wheel/Axle Assembly	1,283 (steel)	763 (Boron/Al)	520	Weight of the Gun
Elevating Screws (2)	147 (steel)	103 each (Ti)	88	Weight of the Gun
Spade (2)	178 (steel)	55 each (Boron/Al)	248	Recoil Force
Cradle/Ballistic Shield	933 (steel and Al)	706 (Boron/Al and Al)	227	Recoil Force
Top Carriage Weldment	850 (Al and steel)	560 (Al and Carbon/Ep)	290	Recoil Force
Top Carriage Parts	61 (steel)	34 (steel)	27	Recoil Force
Bottom Carriage Weldment	1,477 (steel)	538 (Boron/Al)	939	Recoil Force
Trail Weldments (2)	927 (Al)	627 each (Carbon/Ep)	600	Recoil Force
Other Misc. Parts	477 (steel)	264 (Ti and Boron/Al)	213	Some Dependent on Recoil Force
Total	8,108	4,820	3,288	

Two different 9,000-lb artillery pieces are currently being worked by two United Kingdom private contractors, Royal Ordnance and VSEL. The desire for a 9,000-lb system stems originally from a Marine requirement for a 155-mm howitzer capable of replacing all current 105-mm and 155-mm towed artillery systems in service (Foss 1993). Both contractors are working toward this lightweight goal and are attempting to achieve it while maintaining performance equivalent to the M198.

The Royal Ordnance approach to achieving the 9,000-lb goal is two-fold. First, they have designed a curvilinear recoil technique which has the cannon traverse curved rails during recoil, thus taking advantage of gravity and friction to assist with dissipation of the recoiling energy. Absorbing more of the recoiling energy allows for a reduced recoiling mass, which is accomplished by decreasing the gun barrel's wall thickness to more closely match its design to the pressure profile. The second tactic used to reduce the overall system mass is the substitution of titanium for steel in the system components (Foss 1993). Titanium has a mass 56.5% that of steel so its use as a material replacement for various howitzer components provides a substantial weight savings.

VSEL uses a reduced trunnion height as the principal means of reducing the mass of its howitzer design. Lowering the trunnion height greatly reduces the overturning moment of the howitzer during recoil of the barrel. This coupled with VSEL's movement of the breech and cannon far forward (approximately 4 ft) allows the recoiling mass to be reduced to 4,163 lb (by comparison, the M198 has a recoiling mass of 7,000 lb) and the rear trails to be shortened (Floroff et al. 1992).

2. LIGHTWEIGHT HOWITZER STUDY

The M198 155-mm towed howitzer was taken as the baseline system for this study. The study procedure was to implement changes to the M198 in an attempt to reach the 7,000-lb goal weight established as a result of the logistics study. Incorporating the findings of the previous ARDEC and MTL studies on the substitution of lightweight materials for M198 components was a logical first step. As reported in a preceding section, a 25% decrease in mass from the baseline M198 system was deemed possible through the use of composite materials and lightweight metals, resulting in a 12,000-lb (5,443 kg) "M198-equivalent" howitzer.

Other weight saving changes were investigated and adopted where prudent in an attempt to meet the 7,000-lb goal weight. Barrel weight calculations based on estimated fatigue life were made to eliminate

parasitic mass from the cannon tube design. The effect of reducing the maximum cannon breech operating pressure was also examined as a means of facilitating the reduction of barrel weight. A number of techniques to improve the recoil capacity of the howitzer were considered, and soft recoil was chosen for application on the new lightweight howitzer. Geometry changes affecting the howitzer trails, recoil cylinder length, and trunnion height were other aspects explored in the study in an attempt to reduce weight. Finally, tradeoffs of barrel length vs. range were made to allow for even further reduction of the system weight. The subsequent sections detail the specifics of what was considered for each weight savings measure and quantify the projected mass reduction.

2.1 Barrel Weight Reduction. The M198 towed howitzer uses the M199 gun barrel. The barrel weighs 3,850 lb (1,742 kg) (Restifo 1995) and is designed for 11,000 fatigue cycles (Paladin - Office of the Product Manager 1990) and 2,500 cycles in wear (U.S. Army Ballistic Research Laboratory 1991). One reason the barrel has a fatigue life more than four times its wear life is that the recoil system of the M198 requires a large mass for the recoiling parts as a means of absorbing the recoil energy and some of this mass is provided by utilizing an overly thick-walled gun barrel. Thus, substantial reductions in overall system weight are achievable by designing a 155-mm barrel with a reduced fatigue life.

The approach taken here is to determine the optimum barrel design for a specific fatigue life. Since the pressure due to firing a projectile decreases along the length of the gun barrel, the gun barrel should have a tapered form to match the pressure profile. Pressure profiles were generated for several charges of interest for 155-mm howitzers using the IBHVG2 computer code (Anderson and Fickie 1987). From these curves, it was determined that the M203A1, a zone 8s charge, produced the maximum pressure of all the charges with a value of 63.3 ksi (437 MPa). The resulting pressure from the M203A1 was greater than the pressure of the five-increment Modular Artillery Charge System (MACS) along the entire length of the barrel. A comparison of the two pressure profiles is shown in Figure 1.

To investigate the effects of a lower pressure on the weight of a barrel, a second family of charges was considered. Figure 2 shows the pressure profiles generated by the M119A2, a zone 7 charge, and a four-increment MACS. Note that the pressure due to the M119A2 charge is initially greater than the four-increment MACS at the chamber during shot start but subsequently drops below it near muzzle exit. A compilation curve, shown in Figure 2, was generated to design a barrel capable of firing both charges.

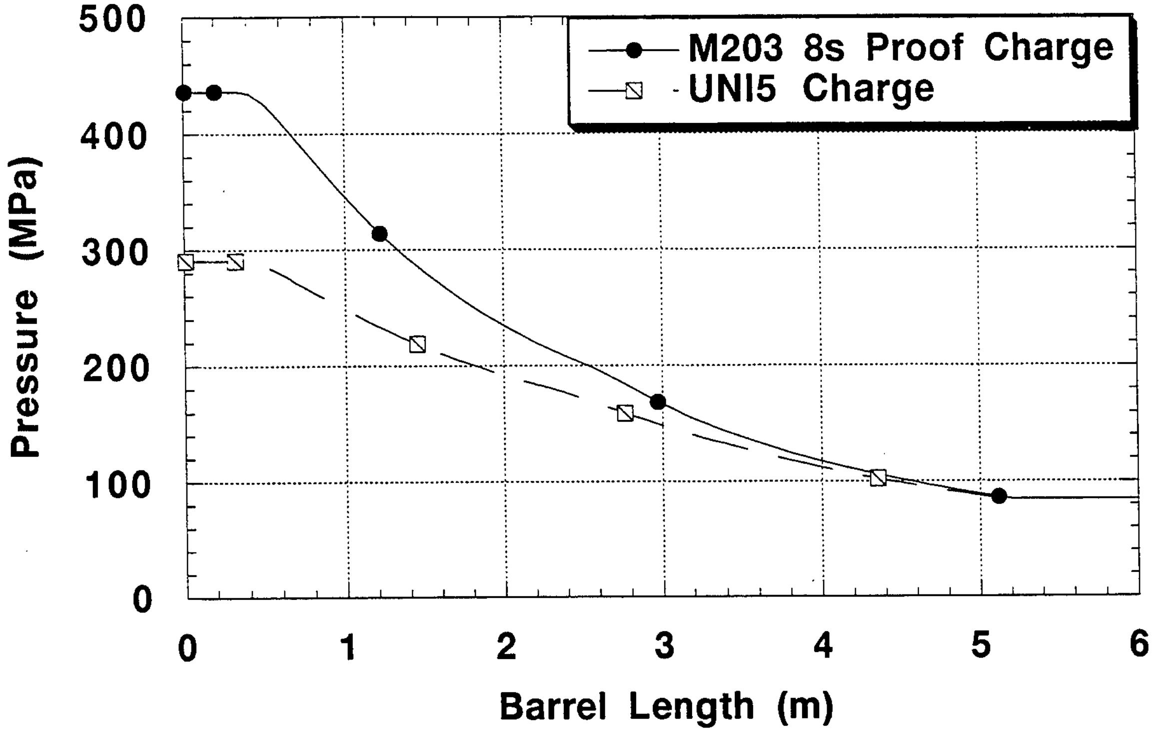

Figure 1. Pressure vs. barrel length for the M203A1 and the five-increment MAC with a 95-lb projectile.

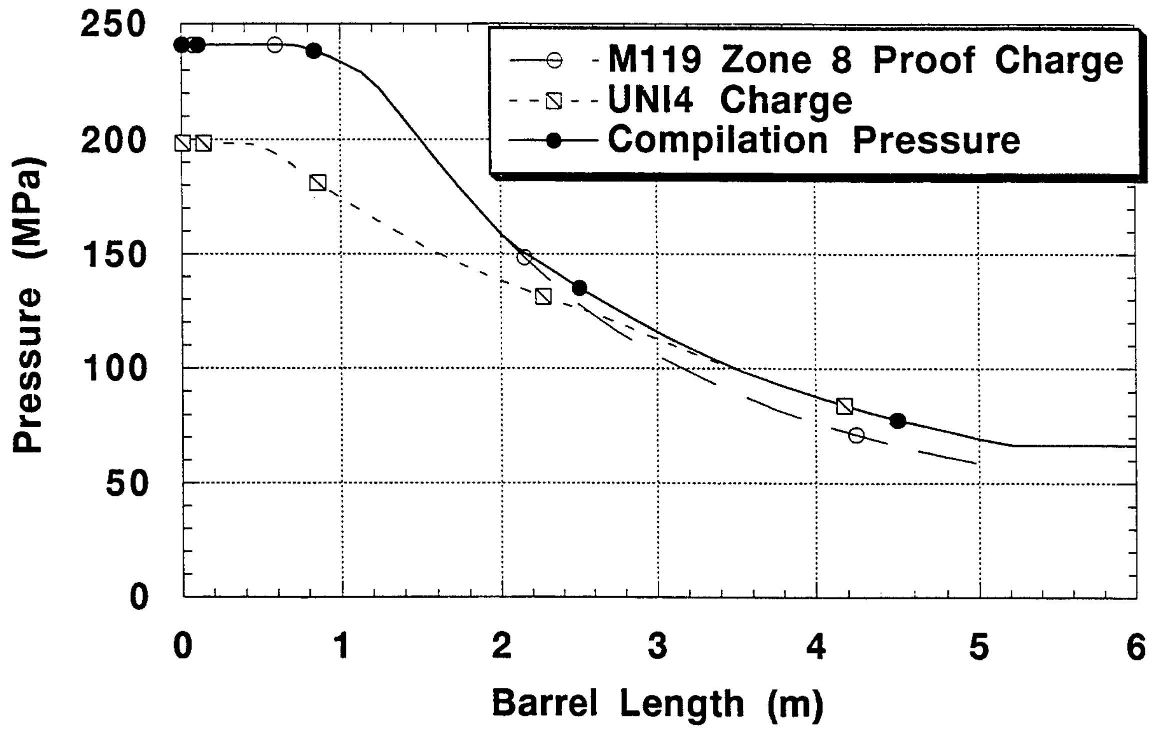

Figure 2. Pressure vs. barrel length for the M119A2 and the four-increment MAC with a 95-lb projectile.

The stress state on the inner surface of a gun barrel with a small crack will depend on the applied pressure profile, crack size, the ratio of the outer barrel radius to the inner radius, and the residual stress due to autofrettage of the barrel. The tensile hoop stress, S_p, at the inner radius of a pressurized cylinder in the region of a stress concentration can be expressed as

$$S_p = -P\left[\frac{(2k_t - 1)\,W^2 + 1}{W^2 - 1}\right], \tag{1}$$

where P is the applied radial pressure, k_t is the local stress concentration factor, and W is the ratio of the outer to inner radius of the gun barrel (Underwood and Parker 1994). It should be noted that if the local stress concentration is equal to 1.0, equation 1 reduces to the Lame' stress for the inner radius of a thick cylinder subject to internal pressure. The maximum residual stress due to autofrettage, S_R, of the gun barrel is expressed as

$$S_R = S_Y k_t\left[1 - \ln W\left(\frac{2W^2}{W^2 - 1}\right)\right] \qquad (\text{if } S_R \le S_Y), \tag{2a}$$

and

$$S_R = S_Y \qquad (\text{if } S_R > S_Y), \tag{2b}$$

where S_Y is the material yield strength, which represents the maximum possible residual stress due to autofrettage.

The effective stress at a crack in the inner radius of an internally pressurized, autofrettaged cylinder can be expressed as

$$S_{eff} = S_p + S_R - P, \tag{3}$$

where S_{eff} is the effective stress at the crack.

Once the stress state at the inner radius is known, the fatigue crack growth rate can be calculated based on the Paris law (Paris, Gomez, and Anderson 1961; Paris 1964), which states the rate of fatigue crack growth is proportional to the range of stress intensity factors at the crack tip. Expressed quantitatively in equation 4 (Ewalds and Wanhill 1989),

$$\frac{da}{dN} = A\,(\Delta K)^m, \tag{4}$$

where da/dN is the crack growth rate, ΔK is the stress intensity factor range ($\Delta K = K_{max} - K_{min}$), and A and m are material constants determined experimentally. The stress intensity factor, K, is proportional to the global stress applied to the cracked area and the square root of the crack length and can be expressed mathematically as

$$K = Y\sigma\sqrt{a}, \tag{5}$$

in which Y is a parameter that accounts for the geometry of the crack, σ is the stress applied to the cracked area, and a is the crack length (Hertzberg 1989).

As a crack grows through the thickness of the gun tube, the crack length will increase some amount, da, with every loading cycle, and the stress intensity factor will increase proportionally. When the stress intensity factor reaches a critical value, the plane strain fracture toughness, K_{1C}, the material will fail catastrophically (Ewalds and Wanhill 1989). The length of the crack at K_{1C} is the critical crack length, a_c, and is expressed as

$$a_c = \left(\frac{K_{1C}}{Y * \sigma_{max}}\right)^2, \tag{6}$$

where σ_{max} is the maximum applied stress.

The fatigue life for the material can then be calculated by integrating equation 4 with respect to the flaw size, a, and the number of cycles, N. The limits of integration on the flaw size are the starting flaw size, a_o, and the final flaw size, a_c. The limits of integration on the number of cycles are the initial number of fatigue cycles, N_i, and the final number of fatigue cycles, N_f. If the initial number of cycles is zero, then the number of cycles to failure can be expressed as follows (Hertzberg 1989):

$$N_f = \frac{2}{(m-2) * A * Y^m \sigma^m}\left[\frac{1}{a_o^{\left(\frac{m-2}{2}\right)}} - \frac{1}{a_c^{\left(\frac{m-2}{2}\right)}}\right]. \tag{7}$$

Equation 7 can be used to predict the number of cycles to failure for a component if the applied stresses, the starting flaw size, a_o, the geometric shape parameter for the flaw, Y, and the various material parameters, A, m, and K_{1c}, are known.

Equation 7 can be solved for the stress-state, σ, to produce a given fatigue, N_f, and may be rewritten as

$$\sigma = \left(\frac{2}{(m-2) * A * Y^{m} N_f} \left[\frac{1}{a_o^{\left(\frac{m-2}{2}\right)}} - \frac{1}{a_c^{\left(\frac{m-2}{2}\right)}} \right] \right)^{\frac{1}{m}} . \tag{8}$$

For a gun barrel with a crack in the inner surface, the stress state, σ, can be set equal to S_{eff} from equation 3. Thus, a relationship is established between the ratio of the outer radius to the inner radius, W, and the fatigue life, N_f. A computer program was written to solve for the minimum ratio of the outer to inner radius to produce a given fatigue life along the pressure curves shown in Figures 1 and 2. The fatigue life constants used in the analysis were taken from other studies on gun tube steels (Underwood and Parker 1994; Parker and Underwood 1994) and are listed in Table 6. The initial flaw size for the analysis was taken as 0.051 in (1.3 mm), which is a typical size flaw due to heat checking in gun barrels (Underwood and Parker 1994).

Table 6. Material Properties of Steel

Property	Value
Elastic Modulus	30×10^6 psi (206.9 GPa)
Yield Strength	171 ksi (1180 MPa)
Y (crack geometry parameter)	$1.12\sqrt{\pi}$
A (crack propagation rate coefficient)	6.52×10^{-12}
m (crack propagation rate exponent)	3.0
K_{1C} (plane strain fracture toughness)	(150 MPa$\sqrt{m}$)
k_t (local stress concentration factor)	1.26
a_o (geometric shape parameter)	0.051 in (0.13 cm)

The weights of gun barrels having fatigue lives ranging from 100 to 100,000 cycles were calculated for the M203A1 charge and the M119A2, which is equivalent to the four-increment MACS. The results are shown graphically in Figure 3, which also depicts the weight and fatigue life for existing barrels. Notice that although the M284, VSEL, Royal Ordnance, and M199 barrels were all designed for the M203A1 charge, their weights are greater than those predicted by the M203A1 curve. This is likely due to a factor of safety margin being incorporated into the barrel design. Since the predictions in this report are based on theoretical equations, which are based on a 50% failure criteria, corrections are needed to predict a reliable design. To provide a margin of safety, the results were normalized to the weight of the VSEL barrel design. Figure 4 shows a plot of these normalized results. Notice that the M199 barrel weight falls on the revised curve, indicating this modification to the calculated data provides a reasonable safety factor.

Further reductions in barrel weight could be achieved by using a composite overwrapped barrel. The U.S. Army Research Laboratory (ARL) has used such barrels in the past to perform single-shot experimental firings with no adverse affect to the composite jacket (Burton, Kaste, and Stobie 1989). More recent research at ARL has focused on the dynamic response of these barrels (Tzeng and Hopkins 1995). However, the technical questions relating to the heat transfer from the steel gun tube to its composite overwrap for repetitive fire is still under investigation. Therefore, since a lightweight howitzer would require a relatively rapid fire rate, this study was limited to an all steel gun barrel design.

2.2 Soft Recoil. Adoption of an improved recoil system was another area investigated in an attempt to reduce the system weight of the towed howitzer. The term soft recoil is used as a designation for the process of imparting forward momentum to the recoil mass, prior to firing the gun, to subsequently reduce the rearward recoil impulse, which must be dissipated by the recoil system.

The rearward impulse is a reaction to the forward acceleration of the projectile, propellant, and propellant combustion gases, and must be dissipated and controlled to maintain weapon stability and structural integrity of the weapon system. A standard technique for dissipating the rearward momentum of a howitzer uses hydropneumatic recoil and recuperator systems, which allow some part of the weapon system to move rearward against a resistive force, thus producing relatively long duration but a lower reactionary force load. This permits the weapon to remain at its firing position without tipping over. The recuperator acts as a temporary storage device, using some of the energy dissipated in the recoil operation to return the recoiling parts forward and positioning them properly for the initiation of the next shot.

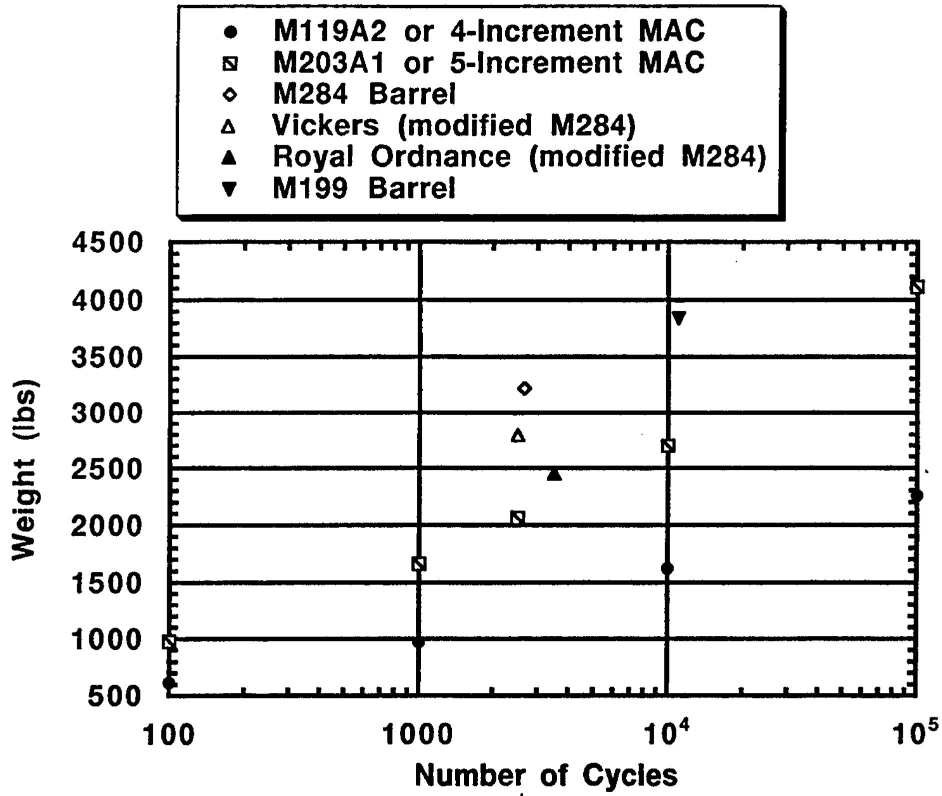

Figure 3. Calculated barrel weights for a fixed fatigue life.

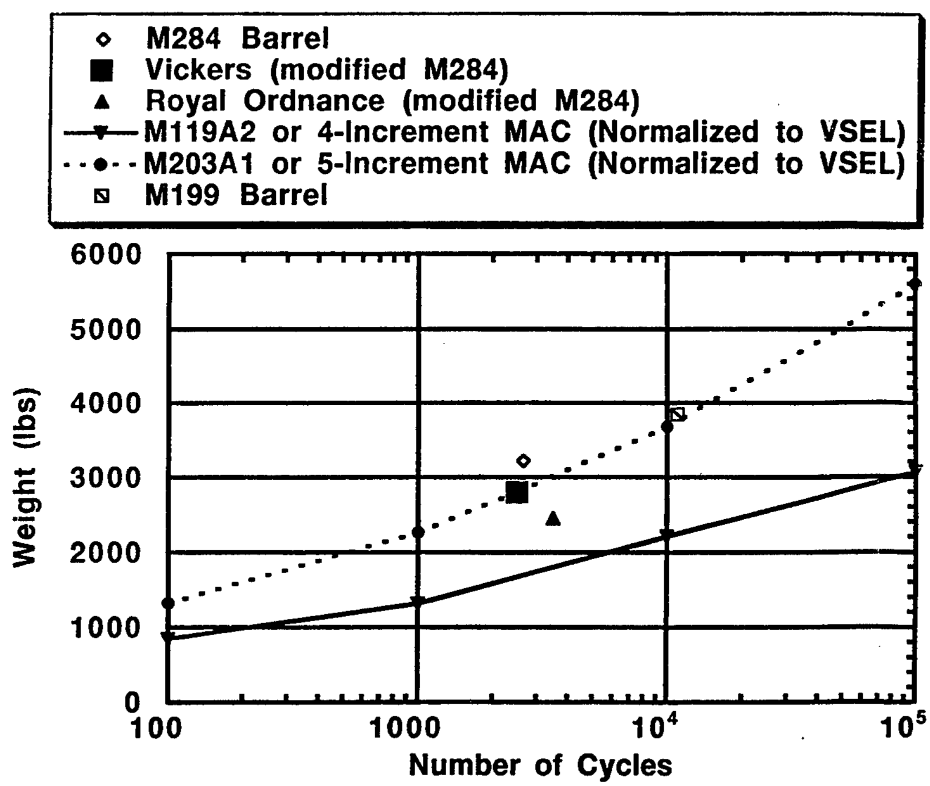

Figure 4. Calculated barrel data normalized to VSEL barrel life.

While a hydropneumatic recoil system acts to control the rearward momentum imparted to the recoiling parts, it does not reduce the magnitude of the rearward impulse. One common method used to reduce the rearward impulse imparted to the recoiling parts is the addition of a muzzle brake to the cannon. The muzzle brake uses the energy of the expelling combustion gases to impart a forward-acting impulse on the gun tube, which reduces the net rearward impulse that must be dissipated by the recoil system. Practical muzzle brakes can use 0.7 to 1.0 times the momentum of the combustion gases to provide a forward-acting impulse on the recoiling parts. Theoretically, even more efficient muzzle brakes could be utilized. However, the forward impulse produced by a muzzle brake comes at the penalty of blast overpressure at the muzzle.

Soft recoil, by imparting forward-acting momentum to the recoiling parts, also reduces the net rearward impulse, which must be dissipated by the recoil system. The magnitude of the forward acting impulse that can be applied has two major constraints. First, the forward impulse applied cannot be more than the rearward impulse resulting from the round being fired. This must be done in order to properly cycle the weapon. More importantly, the second constraint limits the amount of energy available for imparting the forward impulse, for as the magnitude of this stored energy increases, the required strength and size of the system components increase, which is counterproductive to the concept of a reduced-weight weapon system.

Typical impulses for various 155-mm howitzer charges firing a 95.0-lb (43.1 kg) projectile are given in Table 7. These values come from previous work done in examining range-vs.-weight tradeoffs of a 155-mm towed howitzer (Fire Support Armaments Center 1991). The impulses are broken down into various components. I_i is the impulse due to the acceleration of the projectile and propellant in-bore. I_g is the impulse due to expelling combustion gases after the projectile exits the muzzle. I_T, the total impulse, equals the sum of I_i and I_g, while I, the net rearward impulse, equals $I_T - 0.7(I_g)$, where 0.7 is the muzzle brake efficiency.

From Table 7, one can see there is a wide range of values for the total impulse, I, depending on the charge and zone fired. In order to facilitate the use of soft recoil over this range in a practical application, it is necessary to include some compromises. If, for example, the recoil system is designed to allow low-impulse rounds such as the M4A2, zone 3 to be fired without using the soft recoil technique, the forward momentum imparted via a soft recoil system could be increased to accommodate charges such as the M203A1 and M119A2, which produce higher recoil impulses. This compromise alleviates the first system

Table 7. 155-mm Charge Impulse Values

Charge Type	I_i (kN·s) [lb·s]	I_g (kN·s) [lb·s]	I_T (kN·s) [lb·s]	I (kN·s) [lb·s]
M203A1	40.76 [9,174]	14.13 [3,180]	54.89 [12,354]	45.00 [10,128]
M119A2	32.81 [7,384]	9.99 [2,249]	42.80 [9,633]	35.81 [8,059]
M4A2 (zone 7)	25.77 [5,800]	6.10 [1,373]	31.87 [7,173]	27.60 [6,212]
M4A2 (zone 3)	12.11 [2,725]	1.54 [347]	13.65 [3,072]	12.57 [2,830]

constraint discussed previously by maximizing the forward impulse of the soft recoil stroke for high-impulse firings while ensuring sufficient energy is available to return the barrel to the battery position at lower impulse firings.

However, because of the second constraint, it is also necessary to limit the forward impulse from the soft recoil to reduce the amount of stored energy required to impart the momentum to the recoiling parts. For a hydropneumatic system, this keeps the weight down, as well as reduces potential safety and operating problems associated with a weapon having highly loaded activation devices such as springs or pressure cylinders.

For a 155-mm howitzer, a forward impulse of 10.2 kN·s (2,300 lb·s), or about 23% of the high impulse M203A1 charge, seems appropriate. This reduction in impulse combined with the forward impulse contribution from the muzzle brake yields net impulses for dissipation by the recoil system. These resultant impulses are 7,828 lb·s (34.8 kN·s) and 5,759 lb·s (25.6 kN·s) for the M203A1 and M119A2 charges, respectively.

2.3 <u>Geometry Changes</u>. The recoiling mass of the M198 howitzer is 7,000 lb (3,175 kg), divided between the M45 recoil system (2,150 lb [975 kg]) and the M199 cannon assembly (4,850 lb [2,200 kg]) (Medium Artillery Systems Office 1989). The M199 barrel weighs 3,840 lb (1,742 kg), with a muzzle brake weight of 250 lb (113 kg), and a breech weight of 760 lb (345 kg) (Restifo 1995).

The recoil force is calculated as (Fire Support Armaments Center 1991)

$$F_r = \left(\frac{1}{2}\right)\left(\frac{I^2}{m_r\, L_r}\right), \tag{9}$$

where F_r denotes the recoil force, I is the impulse imparted by the cannon to the system, m_r is the mass of the recoiling parts, and L_r is the length of the recoil stroke.

The maximum recoil stroke length of the M198 is 72 in (1.83 m). The maximum ballistic impulse is 10,128 lb·s (45 kN·s) for an M198 equipped with a muzzle brake, firing the M203A1 charge (Fire Support Armaments Center 1991). Substitution of these values into equation 9 yields a recoil force of 39,321 lb (175 kN). This represents the maximum force that must be absorbed during the recoil cycle of the M198 with its current recoil system, the M45.

Benet Laboratories estimated that an improved hydropneumatic recoil system could be designed, resulting in a 1,750-lb (794 kg) recoil mechanism (Fire Support Armaments Center 1991). The mass estimate for the barrel based on the fatigue analysis of section 1.2 is 2,800 lb (1,270 kg), allowing for a cannon with 2,500 cycles to failure (CTF), which is equivalent to the wear life criterion in place for both the M199 and M284 barrels firing the top zone charge, M203A1 (Firing Tables 1991). Royal Ordnance has shown a weight savings of 100 lb (45 kg) can be attained by substituting titanium for the steel when fabricating the muzzle brake. The sum of the recoiling components for this system is listed in Table 8 as Variation A. A similar listing of the M198 baseline is provided for the sake of comparison.

The adoption of a soft recoil system similar to that detailed in the previous section allows for a 2,300-lb·s (10.2 kN·s) reduction in the impulse imparted to the gun system. Incorporating this reduction into the calculation of the recoil force, equation 9 produces a recoil force 23% less than that of the M198. Thus, the M45 recoil system is overdesigned in its capability to handle the recoil requirements of the Variation A howitzer design.

An assumption was made at this point that there is a linear relationship between the recoil length and the weight of the recoil mechanism. It was also assumed that the decrease in the recoil mechanism's load-carrying capacity could be no greater than the percent decrease in the recoil length. For example, based

Table 8. Mass Tradeoff Summary of Cannon and Recoil Assemblies

Variation	Barrel Wgt (lb)	Muzzle Brake, Breech (lb)	Cannon Assemb (lb)	Recoil Mech (lb)	Total Recoil Wgt (lb)	Recoil Force (lb)	Recoil Length (ft)
Baseline M198 155-mm, towed howitzer							
M198	3,840	1,010	4,850	2,150	7,000	39,321	6.0
Reduced barrel weight (2,500 CTF), SR, and lightweight recoil mechanism and muzzle brake							
A	2,800	910	3,710	1,750	5,460	30,115	6.0
11% Reduction of recoil stroke length and mechanism mass, SR							
B	2,800	910	3,710	1,558	5,268	35,070	5.34
2,500-CTF barrel, M119A2 maximum charge, SR							
C	1,700	910	2,610	1,750	4,360	20,412	6.0
20% Reduction of recoil stroke length and mechanism mass, SR							
D	1,700	910	2,610	1,400	4,010	27,742	4.8
29-Caliber, 2,500-CTF Barrel, SR							
E	1,520	910	2,430	1,400	3,830	29,046	4.8

on these assumptions, a 5% reduction in the recoil stroke would result in a 5% reduction in the mass of the recoil mechanism, and the allowable recoil force would be 95% of the original system's.

Employing these assumptions led to Variation B of the howitzer study, which assumed an 11% reduction in recoil stroke with a corresponding mass reduction of the recoil mechanism. The input values for equation 9 are listed in Table 8 along with the calculated recoil force. A comparison of this calculated recoil force to the M198 baseline shows it to be 11% less, nearly equivalent to the assumed reduction in stroke length. This equivalence signifies that further shortening of the recoil system would yield recoil forces in excess of its load-carrying capability.

The result of these calculations was a system whose recoiling mass was 5,268 lb (2,390 kg). Adding this to the weight of the lightweight components from the ARDEC study given in section 1.2 results in a howitzer of approximately 10,000 lb (4,536 kg). Although other weight-reduction techniques were considered, it became apparent that the 7,000-lb goal weight was not attainable while maintaining M198-equivalent performance.

Achieving significant decreases in the weight of the howitzer required that more drastic steps be taken. Thus, the decision was made to pursue a reduced system weight by backing off the high-impulse M203A1 charge. It was recognized that such an approach would decrease the range capability of the system; however, it was deemed the most practical way of attaining the desired goal weight.

The M119A2 was selected to be the maximum allowable charge considered. The M119A2 produces an impulse of 8,059 lb·s (35.8 kN·s) when fired from the M198 with a muzzle brake having an efficiency of 0.7 (Fire Support Armaments Center 1991). Adding in a soft recoil capability equivalent to that assumed previously results in a system impulse of 5,759 lb·s (25.6 kN·s). Reducing the charge allows for a less massive barrel, with the weight of 1,700 lb (771 kg) (taken from Figure 4) for an assumed fatigue life of 2,500 cycles. The input parameters for this 4,360-lb (1978 kg) recoil system are listed as Variation C in Table 8 along with the resulting calculated recoil force. The recoil force is well below the load-carrying capacity of the M45 system due to the ballistic impulse being only about half that of the M198 with the zone 8s charge. This system then requires a much shorter recoil stroke and makes it possible to shorten the recoil mechanism components considerably. Reducing the recoil length by 20% would provide a corresponding decrease in the mass (based on the previous assumption). This variation, D in Table 8, has a shortened recoil mechanism with a weight of 1,400 lb (635 kg) and a recoil force only 76% that of the M198 baseline.

A recoil mechanism having a 1,400-lb mass represents a significant reduction from the M45 recoil mechanism used on the M198. The M45 weighs 2,150 lb (975 kg), and its principal assemblies are tabulated in Table 9 (Medium Artillery Systems Office 1989). Table 9 also provides the mass of various components that make up the M45 (Murray 1995). This is an average value obtained by weighing seven different disassembled M198s. Note that the sum of the component masses is 140 lb (63.5 kg) shy of the 2,150-lb mass quoted for the M45. The shortfall results from not having a mass value for the sleeve bearing assembly, and the mass associated with some smaller components is not listed. A recoil system with a 20% reduction in stroke length would allow for shorter rails, recoil cylinder assemblies, and recuperator cylinder assembly. Applying a comparable 20% mass savings to these components yields a 195-lb (88.4 kg) weight savings. The counterweight can be eliminated, netting an additional 454 lb (210 kg) for a total savings of 649 lb (294 kg). The effect of eliminating the counterweight on the weapon systems stability is addressed in the next section.

Table 9. M45 Recoil Mechanism Component Mass

M45 Recoil Mechanism Component	Component Weight (lb)	Modified Component Weight (lb)
Recuperator Cylinder Assembly	470	376 (20% leng. reduction)
Recoil Cylinder Assembly (2)	271.6 (135.8 ea)	217.3 (20% leng. reduction)
Replenisher Cylinder Assembly	43.6	43.6
Sleeve Bearing Assembly	Not Available	Not Available
Air Cylinder Assembly	70.5	70.5
Rear Yoke	238.8 (steel)	135.0 (Ti)
Middle Yoke	85.7 (steel)	48.5 (Ti)
Front Yoke	141.8 (steel)	80.2 (Ti)
Rails (2)	233.6 (116.8 ea)	186.9 (20% leng. reduction)
Counterweight	454.4	0
Totals	2,010	1,158

Additionally, the three yoke assemblies are steel and have a combined mass of 466.3 lb (211.5 kg). Titanium's density, 0.16 lb/in^3, is 43% less than steel's, which is 0.283 lb/in^3. Direct material substitution of titanium for steel nets an additional mass savings of 202.6 lb (92 kg). Direct substitution of materials is probably somewhat unrealistic since a titanium component would likely need to be larger to provide the same load-carrying capability. However, since the lightweight system will have a lower ballistic impulse due to restricting the system to the less severe M119A2 charge and incorporation of a soft recoil system, the components will be required to carry a reduced load. Therefore, the estimate provided by direct material substitution is deemed reasonable. This savings, plus that achieved by shortening the various recoil components, produces a total mass 850 lb (385 kg) less than the M45, resulting in a 1,300-lb (590 kg) recoil mechanism. This is comparable to the 1,400-lb weight cited earlier and lends some credibility to that estimate.

Still, even with this much lighter recoil mechanism, the total recoil weight stands at 4,010 lb (1,819 kg) (Variation D in Table 8). This was still excessive if we were to achieve a 7,000-lb system capable of being pulled by a 2.5-ton truck. The next consideration to significantly reduce the mass of the recoiling parts was to examine the feasibility of a shorter gun barrel. This represented a departure from the 39-caliber systems presently used by the U.S. Army and its pursuit of even longer 52-caliber cannons (Idelman and Floroff 1994). Interior ballistic code calculations were made using IBHVG2 (Anderson and Fickie 1987) to determine at what length of travel the M119A2 charge completely burns out. It was estimated that shortening the cannon length to 29 caliber would provide 23 caliber of travel and optimize the tube length to the burnout rate of the M119A2 charge. The 29-caliber tube reduces the cannon weight by 180 lb (82 kg). Adopting the 29-caliber barrel provides a means of getting the recoil mass down to approximately 3,830 lb (1,737 kg), which is likely the maximum allowable in order to arrive at an overall 7,000-lb system weight. This system is reflected in Table 8 as Variation E.

The principal means of reducing the recoil was adopting a soft recoil system to lower the rearward impulse of the recoiling parts. This allowed the length of the recoil stroke to be shortened and the overall system weight to be reduced. However, the question arises, "Is such a soft recoil system feasible?" To determine the plausibility of such a soft recoil system design, calculations were made based on soft recoil work done at Rock Island Arsenal (RIA) (Bowrey 1994).

Equation 9 can be used to calculate the driving force needed to impart the forward impulse of the soft recoil process. It is assumed that the forward travel distance is one-third of the rearward recoil travel. Based on Variation E in Table 8, the forward travel length would be 1.6 ft (0.49 m). The recoil mass is 3,830 lb (1,737 kg), and the forward impulse, I, was earlier assumed to be 2,300 lb·s (10.23 kN·s). Employing these values in equation 9 produces a resultant force of 13,898 lb (61.8 kN). Using RIA's estimates for fluid and frictional losses, an additional force of 3,800 lb (16.9 kN) is added for a total required driving force of approximately 17,700 lb (78.7 kN). Using dual 3-in-diameter (76.2 mm) hydraulic cylinders, having a total cross-sectional area of 14.14 in^2 (91.21 cm^2), requires a mean cylinder gas pressure of 1,252 psi (8,631 kPa).

To size the recoil cylinders, it is necessary to calculate the total gas volume. A pressure ratio of 1.35 was assumed over the run-up distance, this value coming from previous RIA calculations (Bowrey 1994). With the following two relationships,

$$\frac{P_2}{P_1} = 1.35 \quad \text{and} \quad \frac{P_2 + P_1}{2} = 1{,}252,$$

the pressure at the end of run-up, P_1, and the pressure at the beginning of run-up, P_2, may be determined. Solving these two equations yields P_1 = 1,065 psi (7,343 kPa) and P_2 = 1,438 psi (9,914 kPa).

The cubic displacement required for the recoil cylinder can be determined from the adiabatic relationship

$$\left(\frac{P_2}{P_1}\right) = \left(\frac{V_1}{V_2}\right)^k, \tag{10}$$

where k has a value of 1.8 for nitrogen. Equation 10 may be rewritten to express V_2 in terms of the difference between V_1 and the cubic displacement, ΔV. Thus we have

$$\left(\frac{V_1}{V_1 - \Delta V}\right)^{1.8} = 1.35. \tag{11}$$

The cubic inch displacement can be expressed as

$$\Delta V = 2L\left(\pi\frac{d^2}{4}\right), \tag{12}$$

where L is the run-up distance (1.6 ft) and d is the diameter of the recoil cylinder (3 in). Substitution of these values into equation 12 yields ΔV = 271 in^3 (4,448 cm^3). Subsequently using this in equation 11 and solving for V_1 produces a value of 1,765 in^3 (0.029 m^3). Since $V_2 = V_1 - \Delta V$, V_2 is found to be 1,494 in^3 (0.0245 m^3).

The volume displaced on the recoil stroke can be calculated using equation 12 and using the recoil travel length of 4.8 ft (1.46 m) as L. With a cylinder diameter of 3 in (76.2 mm), ΔV for the recoil stroke is 814 in^3 (13,344 cm^3).

The gas pressure at the end of recoil, P_3, may be calculated using the form of equation 10 and is calculated as

$$P_3 = 1{,}065 \left(\frac{1{,}765}{1{,}765 - 814} \right)^{1.8} . \tag{13}$$

Multiplying this gas pressure by the total cross-sectional area of the cylinders, 14.14 in^2, gives the resulting load-carrying capability of 45,837 lb (204 kN). The actual recoil force anticipated is listed in Table 8 as 29,046 lb (129.2 kN). Therefore the recoil system will operate as desired under normal operating conditions. The details of firing at nonzero elevation and the timing of round ignition to optimize the forward impulse are beyond the scope of this study. However, it should be noted that major concerns for a soft recoil system are the malfunction conditions that occur when there is either a misfire, and no rearward impulse is applied, or when there is a premature fire, so that the round is fired from the latch position and with no forward impulse imparted. Traditionally, a redundant recoil system has been required to safeguard against these conditions. This approach is costly and undermines the concept of a lightweight howitzer. It is imperative that any secondary backup system be lightweight to minimize the total system weight.

To protect the system from a failure during firing or recoil, it is proposed to place crushable composite tubes both fore and aft of the barrel as shown in Figure 5. The crush tubes behind the breech would dissipate the recoil energy in the event that the soft recoil cycle failed. The smaller crush tubes forward of the breech provide a means of absorbing the energy due to the forward momentum of the gun during the soft recoil cycle in the event of a misfire. A U.S. patent has been applied for on this technology (Hoppel et al. 1996). In general, the purpose of a crushable tube is to absorb energy through the progressive deformation or fracture of material. This process can be enhanced and controlled through the use of composite materials in the construction of the crush tube. Figure 6a (Hull 1991) shows a representative crush tube of length L.

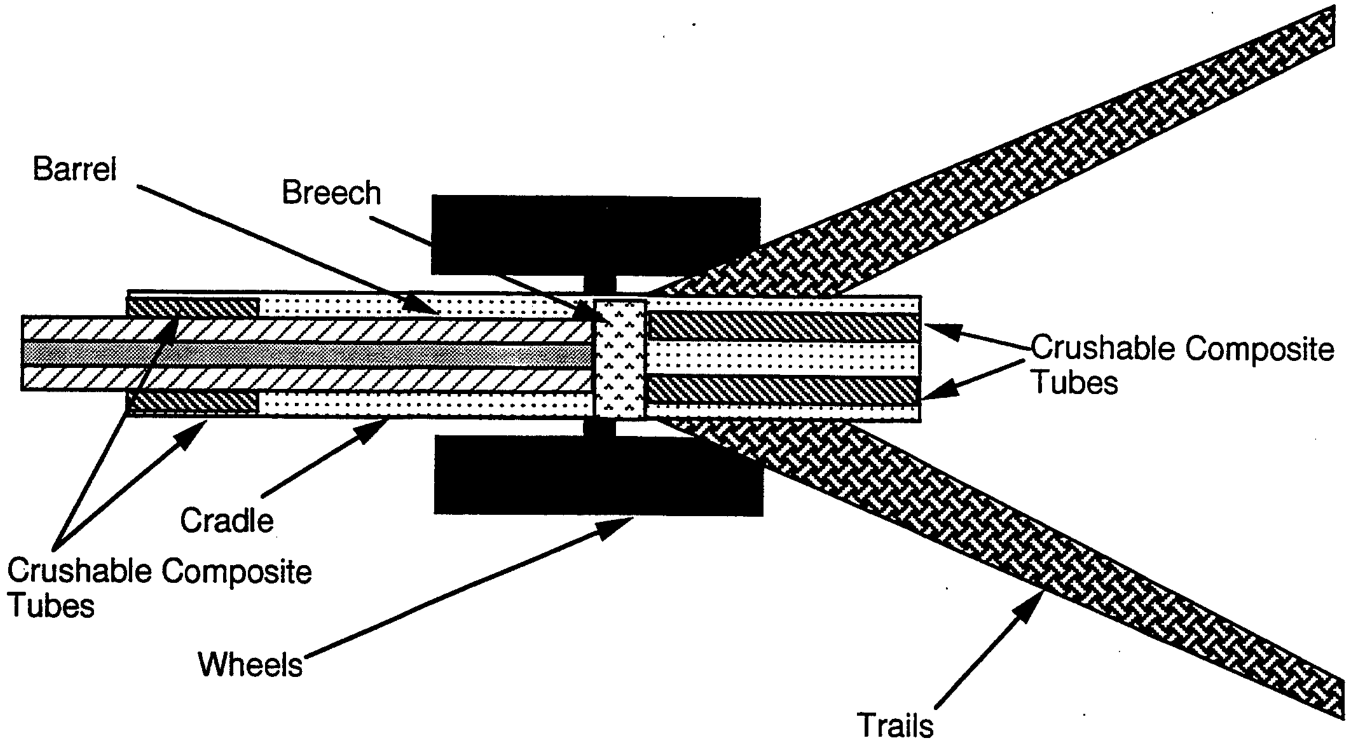

Figure 5. Howitzer equipped with composite crush tubes.

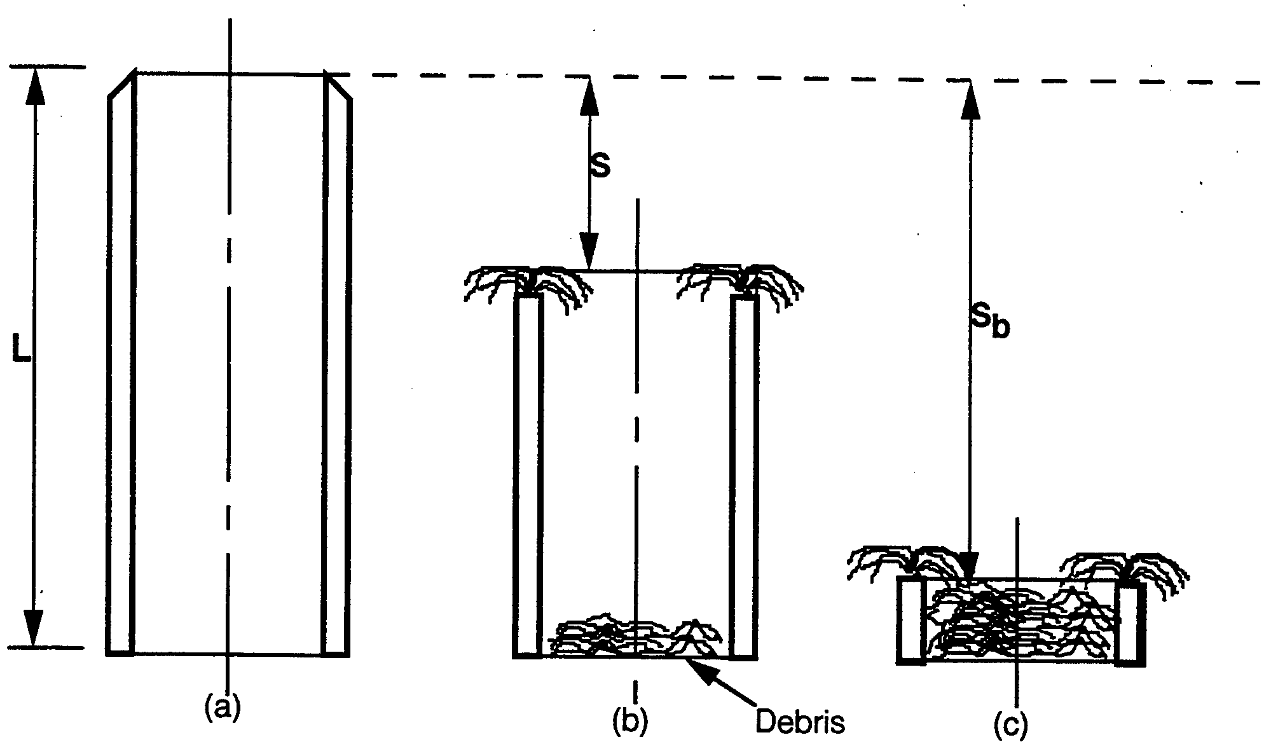

Figure 6. A crushable composite tube design.

The tube shown in Figure 6a is designed with a chamfered end to act as a trigger mechanism to initiate crushing. As the tube is loaded in compression in the axial direction, the material is displaced in the radial direction by a combination of mechanisms including localized fracture and bending (Figure 6b). Crushing should continue in a stable manner until the tube is fully crushed (Figure 6c). Figure 7 shows a representative load vs. displacement curve for the crushing process. Generally, some initial load (P_{max}) is applied to the tube to initiate crushing (stage a). Once crushing is initiated (stage b), the material should absorb energy at a fairly constant rate as the tube is crushed. Once the tube is fully crushed (stage c), the load increases as the material is compacted.

Other advanced recoil mitigation techniques were considered in an attempt to further improve the efficiency of the recoil mechanism. One possible advance currently being researched is the use of electrorheological (ER) fluids, which can be used to increase the viscosity of the fluid in the recoil system to minimize the recoil force. Likewise, "smart" recoil systems that apply a variable braking force, as needed, during the recoil event, are under investigation (Floroff 1994). While both techniques show some promise as a means of mitigating recoil, they were not incorporated into the present study because they are considered to be immature technologies at the present time.

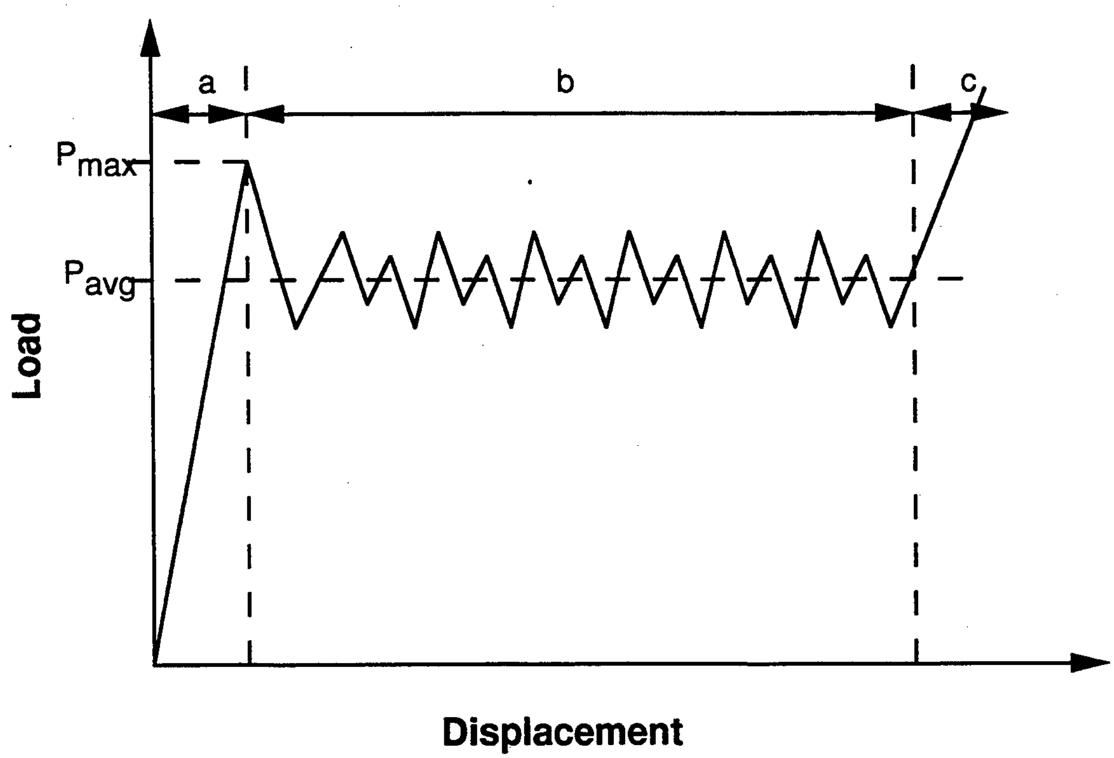

Figure 7. Absorbed load vs. displacement for a composite tube undergoing crushing.

2.4 Barrel Length and Charge Tradeoffs. In order to entirely burn the M119A2 charge in-bore, a minimum travel of 23 caliber is required. This results in a cannon tube having a total length of 29 caliber. The M119A2 requires the greatest length of projectile travel for burnout of all fielded 155-mm charges.

The tradeoff of going to a 29-caliber cannon, of course, is a reduction in the system's effective range. The IBHVG2 code was used to determine the muzzle velocity of a 95-lb (43.1 kg) projectile from 39- and 29-caliber 155-mm cannons with the M119A2 charge.

The M119A2 charge, in the 39-caliber M199 cannon, will fire the 95-lb (43.1 kg) M107 round with a muzzle velocity of 2,260 ft/s (689.0 m/s) to a maximum range of 18,200 m. The muzzle velocity for the M107 round fired with the M119A2 charge from a 29-caliber barrel is 2,080 ft/s (634.6 m/s), resulting in a maximum range of 16,700 m. The reduction in muzzle velocity is approximately 8%. The resulting reduction in range is also about 8%. Range calculations, using muzzle velocities determined from IBHVG2, were made using the General Trajectory Model (GTRAJ3), which is based on firing table data (U.S. Army Ballistic Research Laboratory 1991).

Table 10 presents the range capabilities of the 105-mm M119, a 155-mm with the M199 barrel (39 caliber), and the lightweight 155-mm (29 caliber) howitzers for various projectiles and charges. Although the lightweight 155-mm howitzer's reduced charge capability (use of the M119A2 instead of the M203A1) and shorter barrel reduce its range performance in comparison to the M198, they provide an approximately 19% improvement in range capability over the 105-mm M119 for a non-rocket-assisted launch. For the rocket-assisted (RA) case, the lightweight 155-mm has an 8% improvement in range vs. that of the 105-mm howitzer. The lightweight 155-mm howitzer not only provides a range capability superior to the 105-mm M119, but allows for the carrying of substantially greater mass and volume to increase the lethality of the deliverable payload.

One concern about adopting a shorter length gun barrel is the effect of the blast overpressure exposure on the crew. To address this concern, overpressure calculations were made to see if any deleterious effects were introduced by having a 29-caliber barrel.

Table 10. Range Capability Comparisons

Round	Charge	Range (m)
105-mm M119 Howitzer		
M913 (RA)	M229	20,100
M760	M200	14,000
M444	M67 Zone 7	11,200 (air burst)
155-mm M198 Howitzer (39-caliber M199 Cannon)		
M549A1 (RA)	M203A1	30,300
M549A1 (RA)	M119A2	23,700
M483A1	M119A2	17,800 (air burst)
M107	M119A2	18,200
155-mm Lightweight Howitzer (29 caliber)		
M549A1 (RA)	M119A2	21,800
M483A1	M119A2	16,300 (air burst)
M107	M119A2	16,700

Two sets of calculations were performed. First, the 39-caliber M199 barrel, used on the M198 firing the M203A1 charge, was investigated to provide a baseline comparison. The second case looked at a 29-caliber gun barrel firing the M119A2 charge, the top zone charge for the proposed lightweight system. Both cannons were assumed to employ a muzzle brake with an efficiency equal to 0.7. There was little discernible difference between the resulting pressure contours for the two systems. However, the muzzle being 10 caliber closer to the crew for the 29-caliber gun subjects the crew to a higher sound pressure. The calculations found the level at the rear of the 29-caliber gun to be 30 kPa (4.35 psi) vs. a level of 22 kPa (3.19 psi) at the breech of the 39-caliber system.

MIL-STD-1474D (Department of Defense 1993) sets limits on the maximum permissible impulse noise for an open-air firing of an Army system. To apply the standards, it is necessary to convert the pressure levels to decibels using the following equation (Beranek 1971):

$$\text{Sound Pressure Level} = 20 \log \left(\frac{p}{p_{ref}} \right) \text{dB}, \tag{14}$$

where p_{ref} is the rms sound pressure (2×10^{-5} N/m^2 for airborne sound) and p is the rms sound pressure in N/m^2. Thus, employing the 22,000 N/m^2 and 30,000 N/m^2 sound pressure levels of the 39- and 29-caliber barrels, respectively, in equation 14 yields decibel levels of 180.8 dB and 184.1 dB for the two barrel lengths.

Figure 8 plots lines W, X, Y, and Z to show the allowable exposure limit impulses for various durations. These data are taken directly from MIL-STD-1474D, as is the information in Table 11 that lists the maximum permissible number of exposures per day for the various impulse noise limits for someone wearing both ear plugs and muffs for hearing protection (Department of Defense 1993). Under the guidelines in MIL-STD-1474D, sound pressures above the Z-level are considered to be excessive for military systems.

The sound pressure values for the 29- and 39-caliber gun barrels are shown in Figure 8, and both exceed the Z-level limit imposed by MIL-STD-1474D. Therefore, based on the MIL-STD, both systems are unacceptable. However, the 39-caliber case corresponds to the M198 howitzer, which is a fielded system. Further research found that previous work had identified the M198 as exceeding the allowable impulse noise limits (Salsbury 1981). Salsbury's work helped spur a review of the sound pressure limits by the Office of the Surgeon General and ultimately resulted in proposed changes to Blast Overpressure (BOP) Health Hazardous Assessment (HHA) procedures. These new HHA procedures proposed a new allowable peak impulse level of 187 dB for 100 exposures/day for a system, such as a howitzer, having a B-Duration of less than 60 ms (Department of the Army 1990). The HHA also states that for peak pressure levels below 187 dB, the allowable number of rounds per day will be doubled for each 3-dB decrease. Thus, under the Surgeon General's guidelines, the 29-caliber barrel becomes a viable option for a 155-mm howitzer with an allowance of up to 200 rounds/day for a given gun crew. In addition, it should be noted that rotation of the crew to various weapon service stations would reduce the individual exposures and permit an increase in the allowance of rounds fired per day by a particular crew.

2.5 Further Component Weight Reductions. Combining the recoil system listed as Variation E in Table 8, with a weight of 3,830 lb (1,737 kg), and the howitzer components derived from the ARDEC study listed in Table 5, weighing 4,820 lb (2,186 kg), yields a howitzer with a mass of 8,650 lb (3,924 kg). Further reductions in mass of the howitzer components are achievable because of the reduced system recoil, 26% less than the M198, and the overall lightening of the structure.

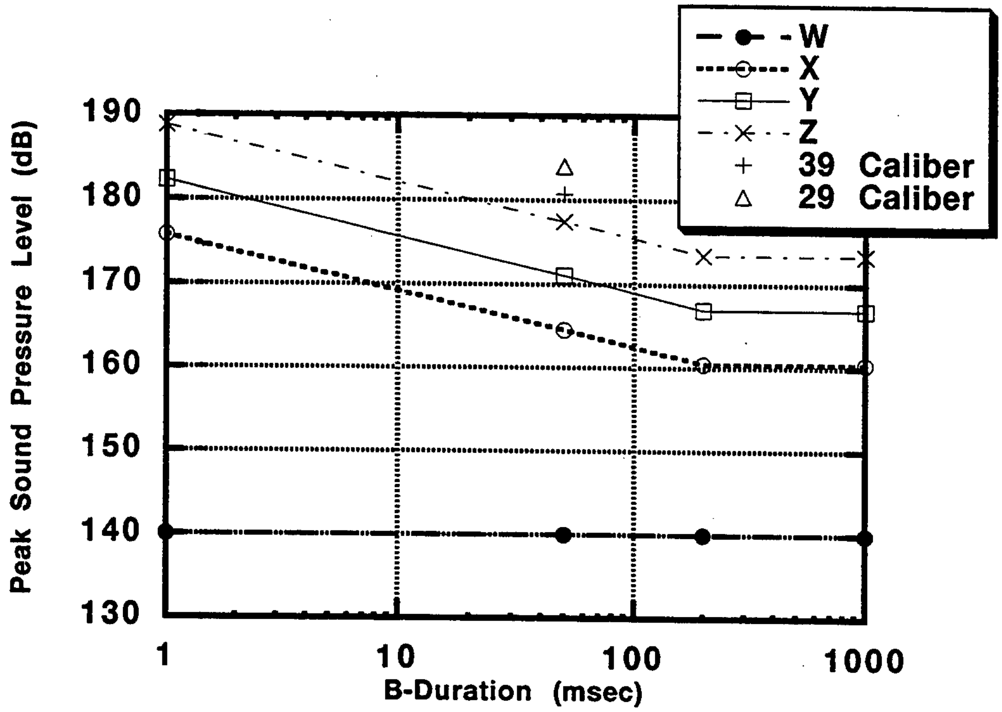

Figure 8. Peak sound pressure limits vs. B-duration for impulse noise.

Table 11. Impulse Noise Daily Exposure Limits

Impulse Noise Limit	Maximum Permissible Number of Exposure/Day		
	No Protection	Either Plugs or Muffs	Both Plugs and Muffs
W	--------Unlimited Exposure --------		
X	0	2,000	40,000
Y	0	100	2,000
Z	0	5	100

The data for the MTL-designed trails in Table 4 may be scaled up to estimate the weight of a trail 12 ft (3.66 m) long. The lightest design in the MTL study weighed 106 lb (48 kg) for a length of 110 in (2.8 m), which scales to 139 lb for a 12-ft design. This represents a significant mass savings from the 627-lb (284 kg) individual trail weight used in the ARDEC study. This translates to a total weight savings of 976 lb (443 kg) for the two trails, thus putting the mass of lightweight howitzer at 7,575 lb (3,426 kg).

Table 5 lists numerous components that may be made less massive due to the reduction in recoil force. With modifications to the trails having already been made previously, the three largest components where weight savings may be attained are the carriage weldments, both top and bottom, and the cradle. Assuming a weight reduction equivalent to the reduction in recoil force, 26%, produces a total weight savings of 469 lb (213 kg).

A final area for consideration of weight reduction is the wheel and axle assembly. The ARDEC study design was based on the wheels and axle supporting the weight of the M198. The lightweight howitzer design has a weight of less than half the M198 so it is reasonable to assume that the wheel and axle assembly weight may be cut in half. This provides another 380-lb (172 kg) weight savings.

Table 12 is a compilation of the various howitzer components and provides a comparison against the ARDEC study values from Table 5. The recoil mechanism is taken from Variation E listed in Table 8. The total system weight for the lightweight howitzer adds up to 6,821 lb (3,094 kg).

Table 12. Lightweight Howitzer Component Masses

System Component	ARDEC Wgt (lb)	LWT How. Wgt (lb)	Basis for Wgt Reduction	5,000 CTF (lb)	Basis for Wgt Reduction
Recoil System and Cannon	—	3,830	Variation E	4,080	5,000 CTF Due to M119A2 Reduced Wear
Trails	627 ea	139 ea	Scaled MTL Design	139 ea.	—
Wheel and Axle Assembly	763	380	50% Reduction in Overall System Weight	380	—
Top Carriage	560	414	26% Reduced Recoil	392	30% Reduced Recoil
Bottom Carriage	538	398	26% Reduced Recoil	377	30% Reduced Recoil
Cradle	706	522	26% Reduced Recoil	494	30% Reduced Recoil
Other Components	999	999	No Change	999	—
Total Weight		6,821	—	7,000	—

This lightweight howitzer design was based on a fatigue life of 2,500 CTF when firing the M119A2 as its top zone charge. The life cycle for the weapon was chosen to be equal to the M198, which is based on the wear criteria of the M199 barrel firing the M203A1. Initially, the lightweight system had equivalent wear and fatigue lives because the analysis began by examining the M203A1 as the top zone charge for the weapon. Later, restriction of the charge to the M119A2 was adopted, and by doing so the wear life of the barrel was doubled because the M119A2 has an equivalent erosion effect one-half that of the M203A1 (U.S. Army Ballistic Research Laboratory 1991). Thus, the system as detailed previously has a fatigue life of 2,500 CTF and a wear life of 5,000 CTF. It is desirable to have the fatigue life be at least as great as that of the wear. Referring back to Figure 4, the barrel weight grows by 250 lb (113 kg) when going from 2,500 to 5,000 CTF as the design criterion. This additional weight puts the system at 7,071 lb (3207 kg), just above goal. However, this additional mass reduces the recoil force on the structure 30% from that of the M198 baseline. Applying a similar percent reduction to the cradle and carriage components in Table 12 results in a mass savings of 71 lb (32 kg). This places the estimated system mass right at 7,000 lb (3175 kg). Further estimates are believed to be achievable by optimizing the sizing of the recoil system, but that was outside the intent of this study.

2.6 <u>Stability Considerations</u>. The analysis has shown that significant mass reductions are achievable on a 155-mm howitzer. One consequence of having a lighter system is it becomes more difficult to minimize the howitzer "jump" or "hop," which necessitates repositioning prior to the next shot and subsequently reduces the firing rate. Thus, it was necessary to determine the 7,000-lb howitzer's stability requirements before declaring it as a realistic possibility.

Figure 9 shows a simple representation of a howitzer. The vector W_w represents the entire system weight acting through the weapon's center of gravity. F_r is the recoil force acting along the axis of the gun barrel. The figure is drawn showing a horizontal firing plane with the height at which the recoil force acts above ground denoted as H. The horizontal or direct-fire position represents the most severe overturning moment and is considered to provide a worst case for the stability analysis. The trail length is shown as L. These parameters are used in the governing stability equation (Fire Support Armaments Center 1991) given as

$$F_r * H < W_w * L. \tag{15}$$

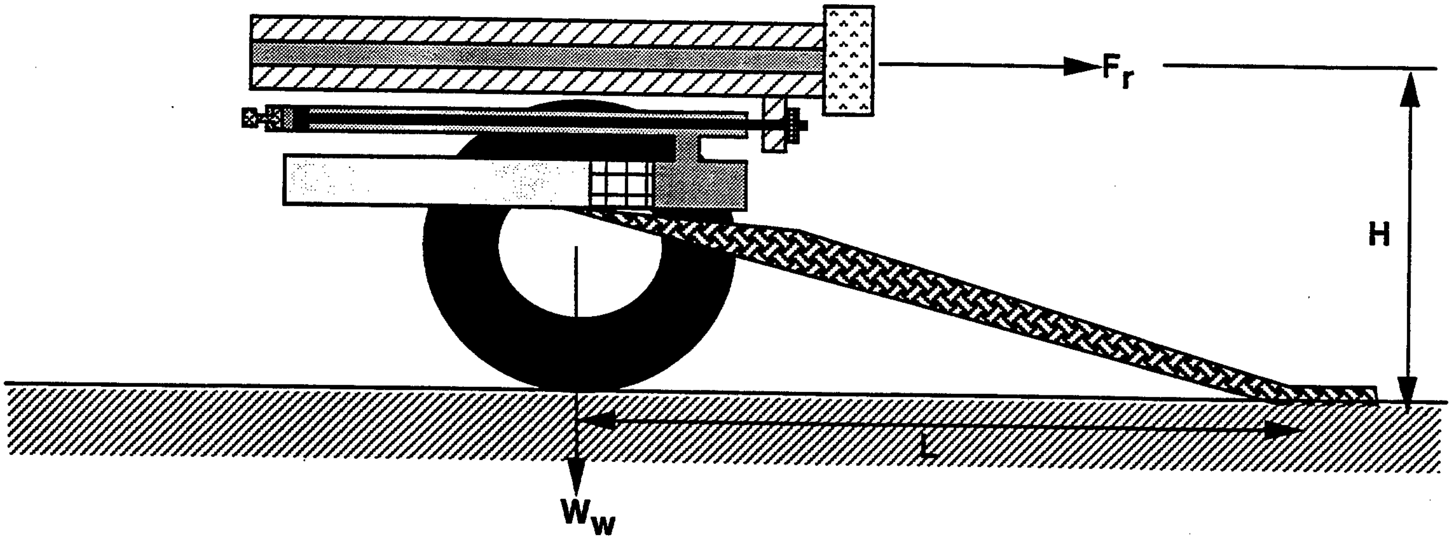

Figure 9. Howitzer sketch with reaction loads.

Equation 15 can be rearranged to

$$H < \frac{W_w * L}{F_r}. \tag{16}$$

Using values from the mass tradeoffs in the previous section, a weapon weight of 7,000 lb, a trail length of 12 ft, and the recoil force from Variation E of Table 8 can be used to calculate the maximum allowable trunnion height. Substitution of the values into equation 16 shows that the lightweight howitzer must have a trunnion height of less than 34.7 in (0.88 m). The current M198 trunnion height is 48 in (1.2 m). However, a lower trunnion height of 25.6 in (0.65 m) has been employed successfully by VSEL (Floroff et al. 1992). Therefore, the 7,000-lb howitzer's stability can be assured with a 30-in (76 cm) trunnion height. The lower trunnion height also provides the added benefit of requiring a smaller and, in turn, less massive lower carriage as was assumed as part of the previous geometry modifications.

3. CONCLUSIONS

The purpose of this study was to identify an artillery system capable of providing the light maneuver forces with 155-mm firepower and lethality while meeting their mobility requirements. A review of the

towing capacity of various vehicles showed that a howitzer weighing 7,000 lb could be towed off-road by a 2.5-ton truck and lifted by a Blackhawk helicopter, thus making it a viable option for a light force unit.

Subsequently, a study was done to see what weight saving measures could be taken to reach the 7,000-lb goal weight. It was hoped that starting with the 15,800-lb M198 system, changes could be implemented to reach the design goal weight while maintaining the range capability.

Use of composite materials and lightweight metals such as titanium provided a 20% mass savings. Tailoring the barrel geometry to more closely match the in-bore pressure profile and incorporating a soft recoil system provided a further weight reduction from the M198 of 10%. Subsequent geometry changes to the rear trails and recoil cylinder were not substantial enough to reduce the projected weight of the howitzer below 8,500 lb (3,856 kg).

Restricting the maximum allowable charge to the M119A2 (as opposed to the M203A1) proved to be the final step needed to reach the desired weight level. The less severe M119A2 charge allowed for a less massive breech and barrel and a shorter caliber cannon and reduced the size of the howitzer support structure. The combination of these changes resulted in a 7,000-lb lightweight howitzer, having a life cycle twice that of the M198, being deemed possible. Limiting the charge to the M119A2 reduced the maximum range of the 155-mm howitzer for a non-rocket-assisted projectile launch from 22.0 to 16.7 km. However, this 16.7-km range still exceeds the capability of the current 105-mm towed howitzer employed by the light forces.

This study, while being purely analytical, used realistic projections based on today's technologies. The results of the study predict that a 7,000-lb howitzer can be designed by adopting composite component parts, adding a soft recoil system, and using the M119A2 as the top zone charge. Such a system would provide 155-mm lethality at ranges beyond those currently attainable by 105-mm howitzers.

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